Final Report
Office of Naval Research
Grant No. N00014-99-1-0928: Year 01

Contributions to the Development of VE-Assisted Training of Spatial Behavior

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01 February 2000

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT DATE	3. DATES COVERED *(From - To)*
02-01-2000	Final Report	15 Jun 1999 - 14 Jan 2000

4. TITLE AND SUBTITLE

Contribution to the Development of
VE-Assisted Training of Spatial Behavior

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-99-1-0928

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Allen, Gary L.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of South Carolina
Columbia, SC 29208

8. PERFORMING ORGANIZATION REPORT NUMBER

Unnumbered

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

ONR

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

Unavailable

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for Public Release; distribution is Unlimited.

13. SUPPLEMENTARY NOTES

None.

14. ABSTRACT

A conceptual analysis for identifying essential spatial skills concluded that three functional "families" of skills can be identified (object identification, wayfinding & orientation, and target interception/interception avoidance) and that current VE technology is sufficient for their assessment and training. An empirical study of frame of reference control indicated that global and local-object frames of reference were more effective than mobile object-based and observer-based frames in fixed observer situations. An empirical study of distance estimation training showed that skill in estimating metric distance can be trained in the field using either verbal or visual feedback and transferred to a novel field setting.

15. SUBJECT TERMS

Assessment, cognition, perception, training, spatial abilities, virtual environments.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPONE NUMBER *(Include area code)*
Unclass.	Unclass.	Unclass.	UP	22	Allen, Gary L. / 803-777-4137

Final Report

Project Title:

Contributions to the Development of VE-Assisted Training of Spatial Behavior

Grant Number N00014-99-1-0928

Year 01

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Summary

"Contributions to the Development of VE-Assisted Training of Spatial Behavior" was an eight-month grant-funded effort that included the following three objectives: A conceptual analysis supporting the development of a battery of essential spatial skills for wayfinding, orientation, and cognitive mapping; an empirical study focusing on observer's ability to use and switch between different spatial frames of reference; and an empirical study of the acquisition and transfer of skill in estimating metric distance in the field. The conceptual analysis was based on the proposition that for training purposes spatial skills should be categorized as functional families of skills. The skill iifamily involved in object identification includes skills such as visual memory, object visualization, flexibility of closure, speed of closure, and mental rotation. The most important members of the skill family concerned with a mobile observer's orientation and localization within an environment are spatial-sequential memory, path integration skill, perspective-taking ability, and configurational learning skill. The most important members of the skill family concerned with the dynamic localization of mobile objects are target-intercept and capture-avoidance skills. Additional considerations suggest that distance estimation, direction estimation, and perhaps map interpretation skills should be added to the list of essential spatial skills.

The empirical study of observer's ability to use and switch between different spatial frames of reference involved the case of a stationary observer verifying the direction of travel of a mobile vehicle. Results of the study support the conclusion that some frames of reference (specifically, references to compass directions and fixed-location objects near the vehicle) are more accurately and more quickly verified than are others (specifically, references to the external stationary observer's orientation). The data suggest that individual observers differ in their facility with different frames of reference. Surprisingly, the findings also indicate that switching from one frame of reference to another of roughly equivalent difficulty was no more costly in terms of time and accuracy than was maintaining a consistent frame of reference.

Results of the study of distance estimation skill showed that skill in estimating viewed distances from a fixed location can be trained rapidly with either direct verbal feedback concerning accuracy or indirect feedback consisting of visual milestones displayed at regular intervals near target sites. Skill acquired through either means transferred readily to a novel setting.

Overall, the project's results offer potential avenues of progress towards the development of VE-assisted training of skilled spatial behavior. The proposed battery of spatial skills could be developed and implemented in collaboration with a VE laboratory. A computerized version of the frame of reference use and switching task could be implemented and the task's predictive validity for map reading or orientation skills assessed. The distance estimation training study lays the groundwork for additional systematic experimentation that would provide a means of VE-based training and a baseline against which such training could be compared.

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1. Introduction

1.1 Background

The work described in this proposal is aimed at contributing to the effort sponsored by the Office of Naval Research to develop highly effective VE-assisted techniques for training and maintaining effective spatial behavior in a variety of tasks relevant to the Navy. As identified in the ONR workshop "Spatial Knowledge Acquisition in Large-Scale Virtual Environments," Monterey, CA, February 1999, these tasks include but are not limited to wayfinding, search, map use, direction and distance estimation, imagined movement and perspective-taking, coordinated movement by spatially distributed teams, and, in general, the integration of various sources of information into a comprehensive spatial representation of a task setting.

Results from a variety of studies have indicated that spatial information about can be acquired effectively through experience in VE's (Darken & Sibert, 1996; Jacobs, Laurance, & Thomas, 1997; Ruddle, Payne, & Jones, 1997; Richardson, Montello, & Hegarty, 1999; Waller, 1999) and that the abilities supporting this learning are similar to those involved in environmental learning under natural circumstances (Richardson et al., 1999). Furthermore, there is evidence of transfer of knowledge from VE-based training to real-world circumstances (Bliss, Tidwell, & Guess, 1998; Waller, Hunt, & Knapp, 1998; Witmer, Bailey, Knerr, & Parsons, 1996). However, there remains a need for basic research on component skills reflected in tasks used in studies such as these. A better understanding of these component skills can result in a valid baseline against which the utility of VE-based training can be assessed and can provide a clearer picture of the VE to real-world transfer of these component skills as well as specific environmental knowledge expressed by means of these skills.

One promising approach to determining the effectiveness of VE-assisted training in the spatial domain is the development of a battery of essential spatial skills for wayfinding, orientation, and environmental learning (also known as "cognitive mapping"). Essential spatial skills are those that (a) have considerable face validity in that they resemble in some obvious ways the tasks performed in real-world settings, (b) have significant predictive validity for a class of tasks performed in real-world settings; and (c) are subject to improvement with training. A task battery of this type could serve as an important assessment tool in evaluating the effectiveness of VE-assisted training by offering one way of comparing pre- and post-training performance.

One of the potential advantages of such a battery would be that it might strike a desirable balance between two approaches to assessment, using "signs" versus "samples." Most standardized ability batteries involve tests with low face validity, modest predictive validity, but reliable generalizability. The tests do not resemble the tasks for which they predict performance, but they reliably account for a small proportion of variance across a range of related tasks. In this situation, high ability scores are a sign of successful training. In contrast, task performance can be predicted using performance on a task that is very much like the criterion task in most aspects. Basically, performance in one task is predicted with a sample of performance from a similar task. In such cases, there is high face validity and typically high predictive validity, but generalizability to other similar

tasks may be quite limited. The goal of a battery of essential spatial skills is to strike a balance between these approaches.

At present, there is no readily available task battery for this purpose. On the one hand, existing evidence suggests that traditional psychometric instruments for assessing spatial abilities, which focus primarily on object perception and imagined manipulation, are at best modestly predictive of spatial performance in larger environments, either real (Allen, Kirasic, Dobson, Long, & Beck, 1996) or virtual (Richardson et al., 1999). On the other hand, very little of the experimental research on spatial cognition has been concerned with the predictive validity of experimental tasks, generalizability of findings, or potential transfer of skills from one situation to another.

Given these considerations, there appears to be ample justification for conceptual and empirical groundwork in support of the development of a battery of essential spatial skills. The effort described in this report represents such groundwork that was feasible with a small allocation of resources within a brief calendar period. The three objectives described below include one objective of a conceptual nature and two dealing with empirical issues. The conceptual objective involves developing a potential framework for selecting tasks for inclusion in a battery of essential spatial skills. The two empirical issues are quite disparate. One focuses on a task for measuring individual differences in the ability to control (i.e., either maintain or switch) spatial frames of reference. The other is concerned with the transfer and training of distance estimation skill.

No task is currently available for assessing individuals' ability to use and switch between spatial frames of reference, although the importance of this issue is rapidly gaining recognition from researchers, as evidenced by discussion at workshops sponsored by the National Center for Geographic Information and Analysis in Santa Barbara, CA, in February, 1999 ("Project Varenius Specialists' Meeting on Multiple Frames of Reference and Multiple Modalities in Representing Spatial Knowledge") and German science foundation in Hamburg in April, 1999 ("International Workshop on Systems of Reference for Spatial Knowledge").

The other empirical objective involves examining the extent to which distance estimation skill can be learned. In this study, the effect of different strategies involving feedback on distance estimation skill will serve as a sample of spatial behavior that may be subject to improvement through general skill learning. Little research has been done to show the efficacy of efforts to improve distance and direction estimation skills in real-world environments. In other words, the extent to which distance estimation skill can be improved through overt learning is pretty much an open question. An empirical study demonstrating such efficacy would serve as a noteworthy prelude to VE-based training efforts dealing with related issues.

1.2 Objectives

1.2.1 *Conceptual Development of a Battery of Essential Spatial Skills.* As indicated previously, this objective involved consideration of existing literature on spatial abilities, with particular interest in VE-based assessment techniques, for the purpose of making a conceptual contribution to the development of a battery of essential spatial skills. In this regard, the distinction

between distinct functional families of spatial abilities was made (Allen, 1999). Essentially, this framework posits several distinct families, or functionally related groups, of spatial abilities. One of these families involves abilities dedicated to object identification; a second to orientation and localization within environments; a third to dynamic localization of mobile objects; and a fourth to localization of events on or very near the body. Given the focus of the current initiative, emphasis will be placed on means of assessing the first, second, and third families of abilities.

In examining existing assessment techniques, suitability of tasks for administration in a VE setting was considered. Clearly, advances are being made in this regard. For example, Rizzo et al.'s (1998) work on mental rotation ability is a VE-based approach involving an ability to identify objects . Work by Jacobs et al. (1997) on place learning, by Loomis, Klatzky, Golledge, and Philbeck (1999) on path integration skills, and by Ruddle et al. (1997) and Richardson et al. (1999) on route learning suggest potential assessment techniques for abilities relating to orientation and locations within environments. A large assortment of video games involves the perception and anticipation of a mobile target's trajectory.

1.2.2 *Empirical Research on Frame of Reference Control.* Thus far, two lines of empirical work on switching frames of reference have been undertaken by different investigators. Carlson-Radvansky has focused on situations involving imagined rotation of single objects (Carlson-Radvansky & Jiang, 1998); Tversky has examined situations in which listeners can use multiple frames of reference when hearing verbal descriptions of environments (Tversky, 1996). The study that was part of this project focused on the conceptual middle ground, that is, the application of multiple frames of reference in a situation involving observation of an object (vehicle) moving in an environment.

Although this situation did not capture all of the possibilities with respect to tasks involving multiple frames of reference and emphasizes verbal communication skills to a significant degree, it was a reasonable point of entry into this conceptual and empirical domain. First, the number of applicable frames of reference that could be compared in this situation was greater than that included in other approaches referred to previously. Second, the situation has face validity in the sense that the task of producing or comprehending verbal descriptions of a vehicle's direction of movement is a meaningful one in some military settings. Third, this task had low technical demands and thus could be completed in a relatively brief period of time.

1.2.3. *Distance Estimation Skill Training.* The focus of this effort is on skill in estimating metric distance to targets viewed from a stationary viewpoint A series of elegant studies by Gibson and her colleagues demonstrated that skill in estimating distance, expressed in standard units, to target objects visible from a specified standpoint can be trained very rapidly using simple feedback or knowledge of results (Gibson & Bergman, 1954; Gibson, Bergman, & Purdy, 1955). Furthermore, Gibson et al. concluded that training of this type did not involve perceptual learning per se; feedback did not lead to greater sensitivity to distance-defining information in the optic array provided by the environment. Instead, increased accuracy in estimating distance was the result of a cognitive process of calibration, which involved relating the information in the optic array to a mode of symbolic

expression involving distance units of equal length. Once the calibration was achieved, it was applicable in different settings.

A critically important issue with respect to the use of VE-based training of spatial skill is whether skill trained in VE can be transferred to field settings. Distance estimation skill is an excellent case in point that can be investigated in a straightforward manner. However, a fair assessment of VE-to-field transfer should have as its comparison the transfer of skills from field to field. The findings from this study help to provide the basis for that comparison.

Also, it is useful to investigate the extent to which the visual nature of VE-based settings lends itself to effective training techniques. The comparison of direct verbal feedback in one experimental condition to indirect visual feedback in another provides insight into the potential effectiveness of visually based means of training estimation skills.

1.3 Relation of Grant Application to Other Ongoing ONR Research

These objectives were intended to supplement and support the ongoing projects by Rudy Darken, Naval Postgraduate School, and Nat Durlach, MIT, and Jack Loomis, University of California--Santa Barbara, as well as the initiative by these researchers and their colleagues to develop a comprehensive research program focusing on the development and implementation of VE-based assessment and training methods. The work reported here is complementary to the goals outlined in the white paper on the possibilities of VE-based training of spatial behavior prepared and submitted to ONR by the team of Nat Durlach, Gary Allen, Rudy Darken, Jack Loomis, and Jim Templeman.

2. Conceptual Development of a Battery of Essential Spatial Skills

2.1 Purpose

The purpose of this conceptual analysis was to produce a list of spatial skills that are may prove to be essential for effective wayfinding and orientation tasks in real-world military settings. As mentioned earlier, ultimately the skills should be found to have (a) have considerable face validity in that they resemble in some obvious ways the tasks performed in real-world settings, (b) have significant predictive validity for a class of tasks performed in real-world settings; and (c) are subject to improvement with training. The idea that a degree of improvement is expected as a function of practice is one of the reasons that the terms "ability" and "skill" are used interchangeably in this context.

The foundation for the conceptual analysis was laid by the proposition that for training purposes spatial abilities should be categorized as several distinct families, or functionally related groups, of spatial skills (Allen, 1999). One of these families concerns situations involving a stationary individual and manipulable objects; this group will be referred to as skills involved in object identification. Another family of skills has to do with situations involving a mobile individual and large, stationary objects; this will be referred to as skills involved in wayfinding and orientation. This third family concerns situations that involves either a stationary or mobile individual and moving objects; these skills are involved in target interception and interception avoidance..

2.2 Skills Involved in Object Identification

As presented in Allen (1999), the spatial abilities most often studied by psychometricians are concerned with interactions between a stationary observer and an object that is small relative to the size of the observer. Quite simply, these abilities involve establishing the identity of an object based on its constituent features under various conditions, such as when the intact object is rotated, when it is only partially visible or manipulable, when it is embedded in a complex background, or when the object is disassembled. All of the evidence suggests that these abilities may be considered to be related in a hierarchy reflecting complexity. Visually based matching of intact objects is at the base of the hierarchy, and anticipation of the appearance of transformed objects is toward the top. It seems reasonable to posit that such abilities evolved as features of a visual-tactile system for detecting the affordances of small objects in proximity to the observer.

As the data show, individuals differ considerably in their performance of tasks requiring these abilities (Lohman, 1988). Sensitivity to visual information about objects is assumed as the foundation for task performance. One source of variation is the speed with which task-relevant features of objects are detected; another source is success in retaining these features in memory temporarily, as necessary. Temporary memory is especially important in more complex tasks in which prescribed changes in the appearance of objects must be anticipated; in such tasks, information is retained temporarily while prescribed transformations are performed. Also, individuals differ in the strategies they employ when complex transformations are required. Regardless of task complexity, prior

experience results in knowledge that dramatically influences performance. Repeated experience with specific objects, which is much more common in everyday life than in psychological research, leads to faster recognition, rotation, and transformation of those objects. Similarly, repeated experience in recognizing, rotating, or transforming a variety of objects results in generalizable skills so that novel objects can be recognized, rotated, or transformed in a specific way.

The psychometric evidence points clearly to the predictive validity of tests that measure these skills for certain jobs, such as architecture, mechanical engineering, and dentistry (McGee, 1979). Although they have not been found to be directly predictive of success in learning the layout of new real-world environments (Allen et al., 1996), they are predictive of the ability to use interfaces for exploring VE's (Waller, 1999). Thus, overall they represent a group of skills of practical significance.

The most important members of the object identification family are those abilities known in the psychometric literature as visual memory (limited to objects in this case); visualization ("object visualization" in this case); flexibility of closure, referring to the ability to detect the object in a visually "noisy" context; speed of closure, referring to the ability to detect partially occluded objects; and mental rotation. VE-based technologies and practical procedures for assessing and training these skills are well within current capabilities. Desk-top virtual displays are well-suited for tasks involving these skills.

2.3 Skills Involved in Orientation and Wayfinding

This family of spatial skills pertains to situations involving mobile individuals within an encompassing environment containing large, immobile objects. These are the abilities that come to mind when wayfinding is mentioned. Sensitivity to available perceptual information--visual, vestibular, tactile, or proprioceptive--provides the foundation for this family of abilities. As indicated in Allen (1999), individual differences in learning environmental layout may be based on differential speed in identifying distinctive environmental objects for use as landmarks and success in retaining these objects in temporary memory long enough to establish their spatial relations to previous encountered reference points. In the case of path integration, differences in working memory capability are particularly salient to success because calculation of the homing vector depends on a record of previous turns and distances. Knowledge stored in long-term memory is also a salient source of variation among individuals. Overt strategies based on prior experience, such as the selection of a frame of reference, can greatly facilitate orientation efforts. Repeated strategy application in specific situations can give rise to orienting schemas, which are expectations that enhance the salience of certain types of information.

Currently available psychometric tests of spatial abilities are not strongly predictive of wayfinding and orientation skill (Allen et al., 1996). However, recent experimental results point to maze learning (Allen et al., 1996), perspective-taking (Allen et al., 1996), and a VE-based spatial orientation test (Waller, 1999) as promising means of assessing and potentially training skills relevant to this group.

Overall, it appears that the most important members of the family concerned with orientation and localization within environments are spatial-sequential memory, path integration skill, perspective-taking ability, and configuration learning skill. VE-based technologies and practical procedures for assessing and training these skills are also within current capabilities, but immersive experiences may be more compelling in some training situations and essential in others.

2.4 Skills Involved in Target Interception and Interception Avoidance

A third family of spatial skills is concerned with observers and mobile objects. These skills are reflected in tests of dynamic spatial skills requiring the anticipation of a target's velocity or trajectory. Actually, for some purposes it may be useful to distinguish between two varieties of dynamic skills, one which involves tracking targets in the visual field and one which pertains to monitoring relations between a mobile individual and a mobile object. The distances involved in these abilities are typically defined by perceptual range.

As indicated by Allen (1999), the most important source of individual variation in these skills is perceptual-motor coordination, central to which is timing. Anticipating an intercept course depends on extrapolating from perceived speed and direction of movement. However, there is a bit more to the story. In the simple case of an object moving through the visual field, anticipating a trajectory intersecting that of a moving object is necessary but insufficient to accomplish the desired results. The more challenging component of the task is to accommodate the speed of the intercepting projectile so that it's arrival coincides with the arrival of the moving object at some point in space, hence the critically important role of perceived temporal duration.

The problem is complicated by observer motion. Judging an intercept course--regardless of whether the goal of the mobile individual is to maintain or avoid such a trajectory--while simultaneously avoiding other objects and perhaps engaging in other activities--fits the description of working memory described earlier. Individuals with prior experience with task-specific objects, either the same moving object or the same projectile, should demonstrate greater skill in such tasks because of greater accuracy in velocity calculations. Similarly, when observer movement is an additional variable, familiarity with task setting and concomitant activities can have the effect of easing the burden on working memory, thus making possible more rapid and accurate computation of intercept course.

The most important members of the family concerned with the dynamic localization of mobile objects are perceptual-motor learning and perceptual-motor coordination, central to which is the timing and sequencing of behavior. Typically, these have been assessed successfully using psychomotor test batteries (Fleishman, 1975). These skills have been trained in simulators for decades, with immersive experiences having some clear advantages in portraying certain spatial situations.

2.5 Additional Skills

The three families of skills mentioned thus far are functionally clustered abilities with clear roots in the adaptive history of the human species. Missing from this group are the skills involved in symbolic communication of spatial information. Included among these skills are the abilities to estimate distance and direction in standard units, to establish a correspondence between map and environment, and to use spatial language effectively. To date, no tests have been shown to be strongly predictive of distance estimation skill (see Allen et al., 1996) or of map interpretation skill.

Because of their potential importance in military task, it seems reasonable to add distance estimation, direction estimation, and perhaps map interpretation skills to the list of essential spatial skills. Current VE-based technologies are adequate for training these skills, but the fidelity of spatial information depicting the environment may prove to be a critical factor in training distance and direction estimation skill. Some of the unique properties of VE technology may be particularly effective in training map interpretation skills.

3. Empirical Study of Frame of Reference Control

3.1 Purpose

This study was aimed at determining differences in the accuracy and speed with which observers could use and switch between different spatial frames of reference. The specific task required observers to verify the direction of a moving vehicle. The following four frames of reference were studied: compass directions, object proximal to the vehicle, the intrinsic axes of the vehicle, and the intrinsic axes of the observer.

3.2 Method

3.2.1 *Participants.* Data were collected from 41 volunteers, 30 women and 11 men, between 17 and 25 years of age. Because of the within-group design of the study, there was a single treatment for all participants.

3.2.2 *Materials and Setting.* A six-by-six block area was represented on a laboratory floor using equally spaced 30 cm squares. The spacing between the squares represented the space necessary for two widths of a toy car, with was approximately 18 cm long and 8 cm wide. Cardinal directions were posted on signs to the north, south, east, and west of the area. At each intersection, a small sign with a printed keyboard symbol (for example, # and &) was attached to the floor in each direction approximately 12 cm from the intersection.

Observers sat in a chair facing the area on the floor. A table containing a computer monitor and keyboard was immediately to their right, so that they could quickly glance from the area on the floor to the computer screen. A computer program was developed to administer a series of queries about the direction in which the toy car turned in the model town. In the program, the frame of reference involving compass directions was referred to as "Compass", those involving the printed symbols at each intersection were referred to as "Symbol", those involving the car's intrinsic axes were referred to as "Car", and those involving the intrinsic axes of the observer were referred to as "You." Accuracy and response time data were recorded using this program.

3.2.3 *Procedure.* The procedure required participants to watch as a model car was manually moved through a series of turns at mock intersections marked on the laboratory floor. After each turn, a test item specifying a spatial frame of reference and an accompanying direction of turn appeared on a computer screen in front of the participant, and he or she had to respond to the statement with a response indicating either "yes" or "no." For example, when the car approached the participant and then turned to the participant's right at an intersection, the participant would respond "yes" if the words "You...Right" appeared on the screen; likewise, "Car.....Left" and "Compass.....East" would be correct answers. The accuracy and response times to correct responses provided the basis for assessing the cognitive effort required for each item.

Initially, participants were presented four blocks of 12 trials in which the frame of reference was consistent (for example, a series of items dealing with the compass directions followed by a series

of items dealing with the participant's left-right orientation). Response times from these trials provided an estimate of each participant's facility with each of the frames of reference involved. Subsequently, items referring to "Compass" and "Symbol" were mixed so that frame switching was required between these two, and items referring to "Car" and "You" were mixed so that frame switching was required between these two. Accuracy and response times from these trials provide an estimate of the cognitive costs (as indicated by an increase in response time when compared to the same item within earlier blocked presentation) of switching frames of reference. There were 12 trials involving each type of switch, that is, "Compass" to "Symbol", "Symbol" to "Compass", "Car" to "You", and "You" to "Car."

3.3 Results

3.3.1 *Differences in Using the Four Frames of Reference*. A one-way ANOVA performed on the proportion of correct responses during the first block of trials in which no switching was required revealed a significant main effect for type of frame of reference, $F\,(3,\,120) = 11.05$, $MSe = 0.04$, $p < .01$. Post-hoc analyses showed that "Compass" (0.83) and "Symbol" (0.78) trials did not differ and resulted in greater accuracy than did either "Car" (0.71) or "You" (0.68) trials. These results are portrayed in Figure 1.

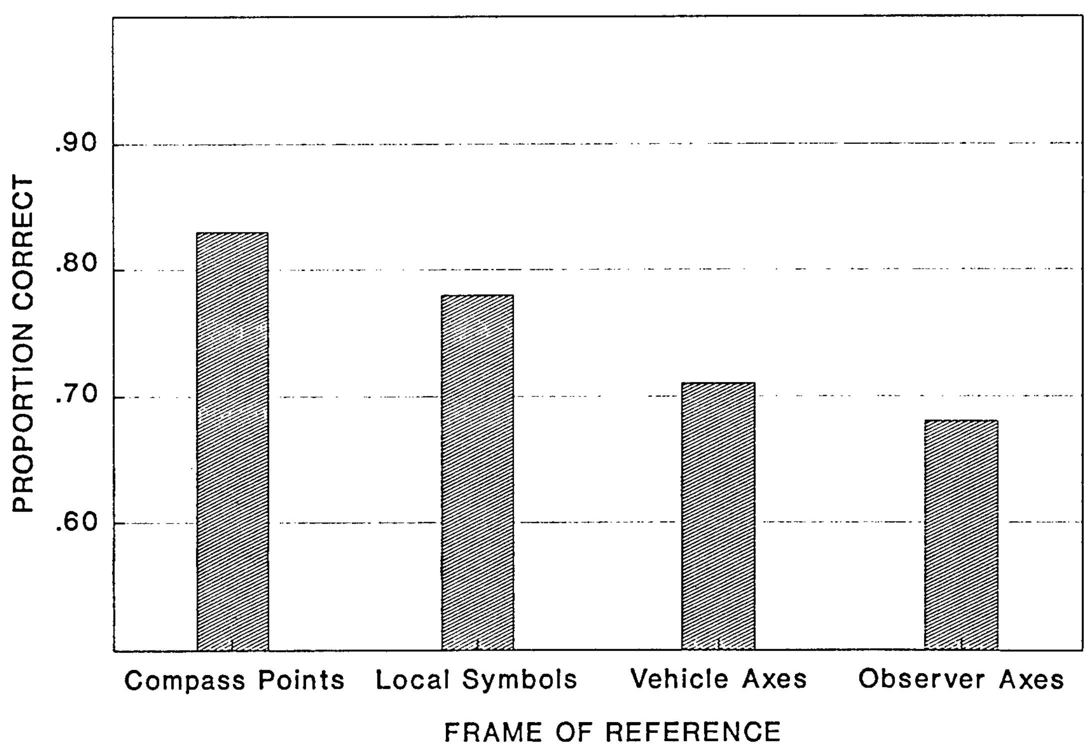

Figure 1. Accuracy in verifying direction of movement using four different frames of reference. Compass points were used on "Compass" trials, local symbols for "Symbol" trials, Vehicle Axes for "Car" trials, and the observer's axes for "You" trials.

A one-way ANOVA performed on the response times from trials with correct responses revealed a main effect for type of frame of reference, F (3, 120) = 2.88, MSe = 881056, $p < .05$. Post-hoc analyses showed that observers responded more rapidly to "Symbol" (2324 ms), "Car" (2341 ms), and "Compass" (2412 ms) trials than to "You" trials (2851 ms), with no difference between the initial three.

Referring to accuracy scores, participants were divided into groups based on the frame of reference that resulted in the greatest accuracy. Individuals were unequally distributed across the groups, with 18 performing best on "Compass" trials, 18 on "Symbol" trials, 3 on "Car" trials, and only 2 on "You" trials.

3.3.2 *Cognitive Costs of Switching Frames of Reference*. For these analyses, the accuracy and response times resulting from trials that required switching frames of reference were compared to the accuracy and response times resulting from matched trials when no change of reference frame was involved. The 2 (Frame of Reference Type: "Compass" versus "Symbol") x 2 (Consistency of Frame of Reference: blocked versus mixed trials) ANOVA performed on proportion correct scores revealed main effects for Frame of Reference Type, F (1, 40) = 22.34, MSe = 0.03, $p < 0.001$, and for Consistency, F (1, 40) = 5.77, MSe = .03, $p < 0.05$. The interaction was not significant. The main effects showed that accuracy with "Compass" trials (.92) was great than was accuracy with "Symbol" trials (.76), and that trials requiring a switch between the two frames of reference resulted in greater accuracy than did trials requiring the maintenance of a frame of reference (.88 versus .80).

The corresponding 2 x 2 ANOVA performed on response times showed no significant main effects or interactions. The grand mean response time was 1850 ms.

The 2 (Frame of Reference Type: "You" versus "Car") x 2 (Consistency of Frame of Reference: Blocked versus mixed trials) ANOVA performed on proportion correct scores yielded a significant effect of Frame of Reference Type, F (1, 40) = 5.64, MSe = 0.04, $p < 0.05$, but neither the other main effect nor the interaction was significant. The main effect reflected the fact that accuracy was greater with "You" trials (.84) than with "Car" trials (.74).

The corresponding 2 x 2 ANOVA performed on response times showed no significant main effects or interactions. The grand mean response time was 2186 ms.

3.4 Discussion

Results of the study support the conclusion that some frames of reference are more accurately and quickly accessed than are others when fixed-position observers comprehend the direction of a vehicle moving in their field of view. Specifically, accuracy was greater with directions described in terms of compass directions and fixed-location objects near the vehicle rather than with direction described in terms of the axes of either the vehicle itself or the observer. Response time data corroborate the difficulty observers had with verifying directions in terms of their own

orientation in the room. Clearly, confusion between left and right, as well as interference between the car's axes and those of the observer, could be responsible for these results.

Dividing the observers into groups based on the frame of reference that resulted in the greatest accuracy for each individual showed clearly that (a) observers tended to perform most accurately with either compass directions or local objects near the mobile vehicle, and (b) there was an equal split between these two frames of reference in terms of the number of observers who performed best with each.

Surprisingly, the trials in which switching from one frame of reference to another was involved indicated that there was virtually no cognitive cost involved in such switches. Switching between compass directions and directions based on local objects did not result in significantly reduced accuracy or longer response times. Neither did switching between the vehicle's intrinsic axes and the axes of the stationary observer. This finding was unexpected and somewhat counter-intuitive. However, it must be emphasized that the two instances of frame-switching studied thus far involved changing between two frames of reference of roughly equal difficulty as reflected in accuracy data. Future research should be aimed at switches between reference frames that are of different difficulty.

Overall, the findings suggest that this frame of reference task is an informative measure of spatial skill, the predictive validity of which should be determined in future research. A fixed observer version of this task would be easily adapted to desk-top VE presentation; a mobile observer version of the task would be more effectively presented in an immersive display.

4. Empirical Study of Distance Estimation Skill Training

4.1 Purpose

This study was designed to investigate the relative effectiveness of two means of training distance estimation skill and to examine the extent to which skill acquired by either method would transfer from one field setting to another. The two means of training differed in terms of the type of feedback provided to observers estimating distances in meters from stationary positions to target locations roughly 30 to 300 m away. One group of participants received direct verbal feedback in terms of the correct number of meters from the observation position to the target; another group received indirect visual feedback in the form of a set of visual markers ("milestones") placed at equal intervals bracketing the target.

4.2 Method

4.2.1 *Participants.* Data were collected from 41 university students ranging in age from 17 to 25 years of age. Participants were assigned at random to one of the three following treatment groups: Direct Verbal Feedback (3 men, 9 women), Indirect Visual Feedback (2 men, 11 women), and No Feedback (3 men, 13 women).

4.2.2 *Materials and Experimental Setting.* The experiment took place in two large adjacent fields used as parking lots. One field served as the training setting; the other served as the transfer of training setting. In the training setting, two sets of distance estimation trials were prepared prior to data collection. Each set consisted of 10 distinct standpoints, each associated with a particular target location. The target distances ranged from 30 to 300 m in 30 m intervals. Exact distances included a randomly generated number 1-9 either added or subtracted from the interval. Thus, the first set of trials involved targets 28, 61, 92, 127, 141, 173, 212, 239, 265, and 305 m from the designated standpoints; the second set involved targets 35, 56, 88, 114, 153, 175, 204, 249, 262, and 293 m from the designated standpoints. In the test setting, one set of distance estimation trials was prepared. This set involved targets 32, 67, 82, 123, 144, 189, 201, 239, 264, and 291 m from the designated standpoints. For all estimation trials, an octagonally shaped stop sign .7 m wide served as the target.

Direct verbal feedback involved informing participants of the exact target to distance expressed in m. Indirect visual feedback involved participants seeing the target with visual milestones at the two nearest 50-m intervals from the standpoint that preceded the target and that followed the target. For example, if the target was 173 m from the standpoint, visual milestones were placed at 100 m, 150 m, 200 m, and 250 m from the standpoint. Bright orange traffic cones 0.8 m tall served as visual milestones.

Participants estimated all distances in m by writing their estimates on small color-coded pieces of paper. A meter stick was placed on the ground in front of them as a reference for each estimate.

4.2.3 *Procedure*. Participants were tested in groups of from four to eight individuals. Transportation was provided from the university campus to the field settings where data were collected. After being briefed with regard to the purpose of the study, participants provided the first set of distance estimates. During the procedure, one experimenter escorted participants to each standpoint in succession and instructed them to face in a certain direction, which was always away from location of the target on the trial that immediately followed. A second experimenter fixed the corresponding target for each trial in succession. When each target location was fixed by the second experimenter, the first experimenter instructed the participants to turn, refer to the meter stick on the ground, and estimate the distance to the target. Estimates were collected after each trial so that prior estimates were not available to participants on subsequent estimates.

All participants completed the first set of estimates without feedback. During the second set, participants in the Direct Verbal Feedback condition were told after each trial the exact distance in meters to the target, those in the Indirect Visual Feedback condition viewed the visual milestones before and after the target location, and those in the No Feedback condition received no information about the accuracy of their estimates. Participants seeing the visual milestones were told the distance to the nearest milestone and were informed that all milestones were 50 m apart.

After the second set of estimates, the experimenters escorted the participants to the second field for a third set of distance estimation trials. None of the participants received feedback regarding the accuracy of their estimates during the third set. When the third set was completed, the participants were debriefed and transported back to the university campus.

4.3 Results

The primary analysis for the distance estimation data was a 3 (Feedback Condition) x 3 (Target Set) mixed analysis of variance (ANOVA) performed on the absolute error of estimates (in meters). For this analysis, data from two participants were omitted as outlying data points that severely skewed the distribution of estimates in the first set. The results yielded significant main effects of Feedback Condition, $F(2, 38) = 31.88$, $MSe = 57467$, $p < .001$ and Target Set, $F(2, 76) = 10.46$, $MSe = 6604$, $p < .001$, and a significant interaction between these factors, $F(4, 76) = 6.01$, $MSe = 6604$, $< .001$. Mean distance estimation errors are shown in Figure 1. Post-hoc comparisons showed that mean error did not changed across target sets for the No Feedback condition, but it was reduced significantly from the first to the second and third target sets for both the Direct-Verbal Feedback and the Indirect-Visual Feedback conditions. The two groups that received feedback did not differ for either the second or third target sets.

4.4 Discussion

The evidence indicates that skill in estimating distances up to 300 m in terms of standard units (meters in this case) can be trained rapidly by providing either direct verbal feedback or indirect visual feedback after estimates. The difference between the two feedback conditions was not significant, suggesting that simply seeing visual milestones is sufficient for viewers to calibrate their estimates of

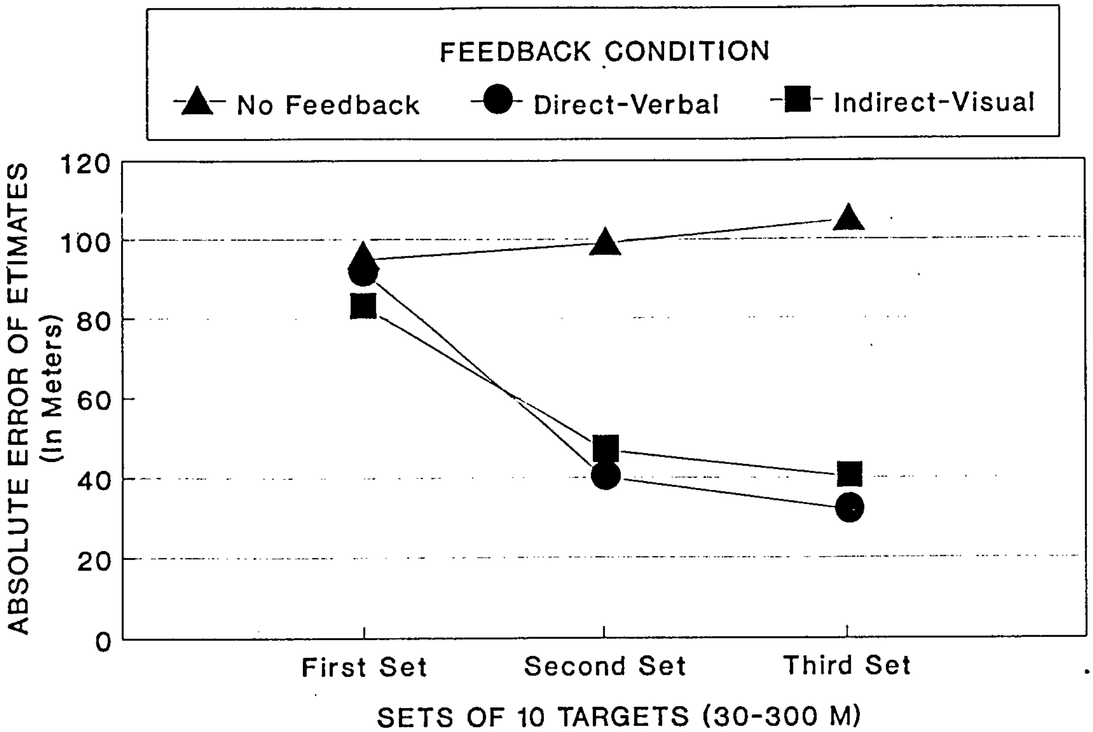

Figure 2. Mean absolute error of distance estimates for three treatment conditions. No feedback was provided on Set 1, which provided a baseline, or on Set 3, which was a test of skill transfer.

viewed distance. The findings further support the conclusion that skill acquired by either means readily transfers to a similar but novel field setting. The data indicated clearly that practice in estimating distances in different settings without feedback or knowledge of results does not result in the acquisition of distance estimation skill. Unanswered questions include the extent to which distance estimation skill transfers to different terrain types, the longevity of skill acquired through "single-shot" training, and, most important in terms of using VE-based technology, the utility and tranferability of distance estimation skill acquired through pictorial or virtual displays.

5. Conclusions

5.1 Essential Spatial Skills

The conceptual analysis aimed at developing a battery of essential spatial skills leads to the following conclusions:

- Essential spatial skills can be organized into functional families, with the most relevant ones for military purposes being "families" involved in object identification, orientation and wayfinding in large-scale spaces, and target interception/interception avoidance.

- The family of skills involved in object identification include object visualization, mental rotation of objects, visual memory for objects, speed of closure, flexibility of closure.

- Developing and implementing VE-based assessment and training tasks for object identification skills is feasible and readily accomplished with widely available desk-top technology.

- The family of abilities involved in orientation and wayfinding in large-scale spaces include spatial-sequential memory, path integration skill, perspective-taking skill, and configuration learning skill.

- Developing and implementing VE-based assessment and training tasks for orientation and wayfinding skills is feasible but requires visual displays that simulate presence in and movement through environments.

- The family of abilities involved in target interception/interception avoidance include perceptual-motor learning skills, perceptual-motor coordination, timing and other skills readily assessed using psychomotor batteries.

- Developing and implementing assessment and training tasks for target interception/ interception avoidance skills is a well-practiced art in the special case of pilot selection and training. Less resource-intensive VE-based tasks for ground-based maneuvers seem feasible.

5.2 Frame of Reference Control

The empirical study of frame-of-reference control led to the follow conclusions regarding the use of different spatial frames of reference when a stationary observer comprehended the direction of a mobile vehicle from a fixed viewpoint:

- A global abstract frame of reference (i.e., compass directions) and a local object-based frame of reference (i.e., stationary objects proximal to the vehicle) are most effective in terms of accuracy and speed of processing.

- The frames of reference provided by the observer's intrinsic axes (i.e., left, right, away, and toward) and by the vehicle's intrinsic axes (i.e, left, right, straight, and back) are less effective in terms of accuracy.

- Switching from one effective frame of reference to another effective frame of reference or from one less effective frame of reference to another less effective frame of reference had no apparent cognitive cost in terms of accuracy of performance or processing time.

- Success in frame of reference control should be investigated as a potential indicator of general skill in comprehending and communicating orientation information.

5.3 Training Distance Estimation Skill

The following conclusions are based on the field experiment of the acquisition and transfer of skill in estimating 30-300 m distances in meters from a fixed point of view:

- Skill in making accurate estimates of metric distance is acquired rapidly using either direct-verbal feedback (i.e, providing the accurate distance to target during training) or indirect-visual feedback (i.e., providing visual milestones near the target).

- Indirect-visual feedback was as effective as direct-verbal feedback in this instance.

- Distance estimation skill acquired through either means of feedback transferred readily to a novel field setting.

- The effective training observed in this instance provides a baseline for comparing the effectiveness of feedback-based training using pictorial or virtual displays.

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